Chapter 1 - All about matter

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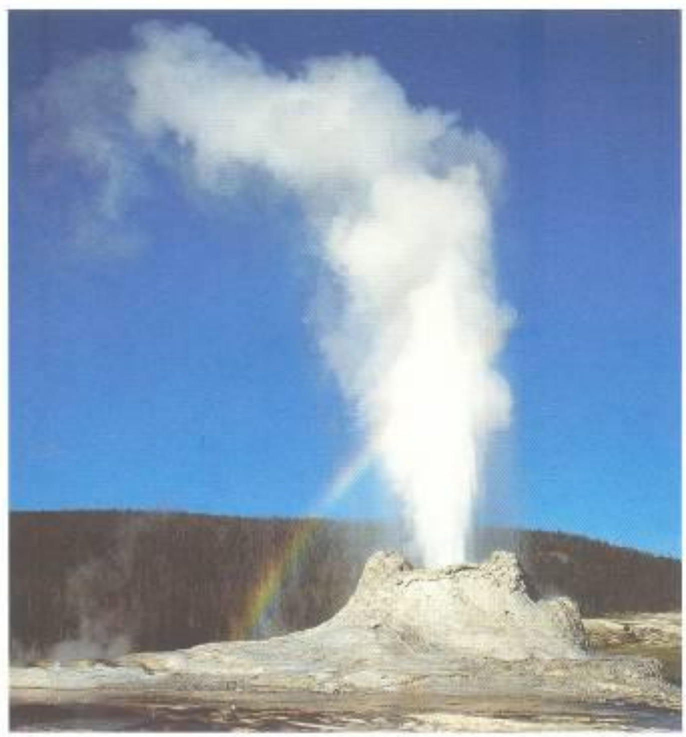
Chemistry is about what **matter** is like and how it behaves, and our explanations and predictions of its behaviour. What is matter? This word is used to cover all the substances and materials from which the physical universe is composed. There are many millions of different substances known, and all of them can be categorised as solids, liquids or gases (Figure 1.1). These are what we call the **three states of matter**.

a solid

b liquid



c gas

Solids, liquids and gases

A **solid**, at a given temperature, has a definite volume and shape which may be affected by changes in temperature. Solids usually increase slightly in size when heated (**expansion**) (Figure 1.2) and usually decrease in size if cooled (**contraction**).

Figure 1.2 Without expansion gaps between the rails, the track would buckle in hot weather.

A **liquid**, at a given temperature, has a fixed volume and will take up the shape of any container into which it is poured. Like a solid, a liquid's volume is slightly affected by changes in temperature.

A **gas**, at a given temperature, has neither a definite shape nor a definite volume. It will take up the shape of any container into which it is placed and will spread out evenly within it. Unlike those of solids and liquids, the volumes of gases are affected quite markedly by changes in temperature.

Liquids and gases, unlike solids, are relatively **compressible**. This means that their volume can be reduced by the application of pressure. Gases are much more compressible than liquids.

The kinetic theory of matter

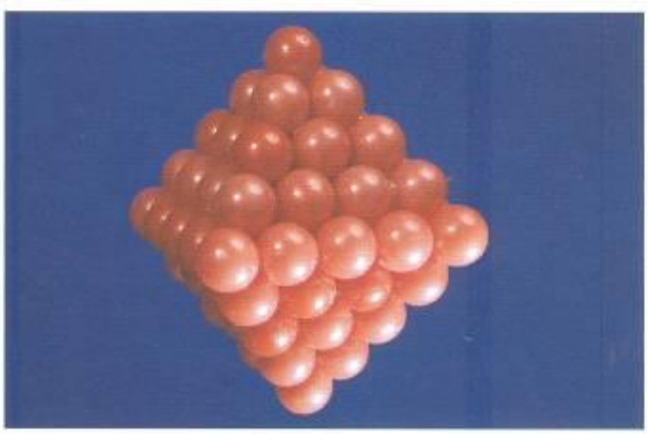
The **kinetic theory** helps to explain the way in which matter behaves. The evidence is consistent with the idea that all matter is made up of tiny **particles**. This theory explains the physical properties of matter in terms of the movement of its constituent particles.

The main points of the theory are:

- all matter is made up of tiny, moving particles, invisible to the naked eye. Different substances have different types of particles (atoms, molecules or ions) which have different sizes

- the particles move all the time. The higher the temperature, the faster they move on average

- heavier particles move more slowly than lighter ones at a given temperature.



a A model of a chrome alum crystal.

b An actual chrome alum crystal.

Figure 1.3

The kinetic theory can be used as a scientific model to explain how the arrangement of particles relates to the properties of the three states of matter.

Explaining the states of matter

In a solid the particles attract one another. There are attractive forces between the particles which hold them close together. The particles have little freedom of movement and can only vibrate about a fixed position. They are arranged in a regular manner, which explains why many solids form crystals.

It is possible to model such crystals by using spheres to represent the particles (Figure 1.3a). If the spheres are built up in a regular way then the shape compares very closely with that of a part of a chrome alum crystal (Figure 1.3b).

Figure 1.4 A modern X-ray crystallography instrument, used for studying crystal structure.

Studies using X-ray crystallography (Figure 1.4) have confirmed how the particles are arranged in crystal structures. When crystals of a pure substance form under a given set of conditions, the particles present are always packed in the same way. However, the particles may be packed in different ways in crystals of different substances. For example, common salt (sodium chloride) has its particles arranged to give cubic crystals as shown in Figure 1.5.

Figure 1.5 Sodium chloride crystals.

In a liquid the particles are still close together but they move around in a random way and often collide with one another. The forces of attraction between the particles in a liquid are weaker than those in

a solid. Particles in the liquid form of a substance have more energy on average than the particles in the solid form of the same substance.

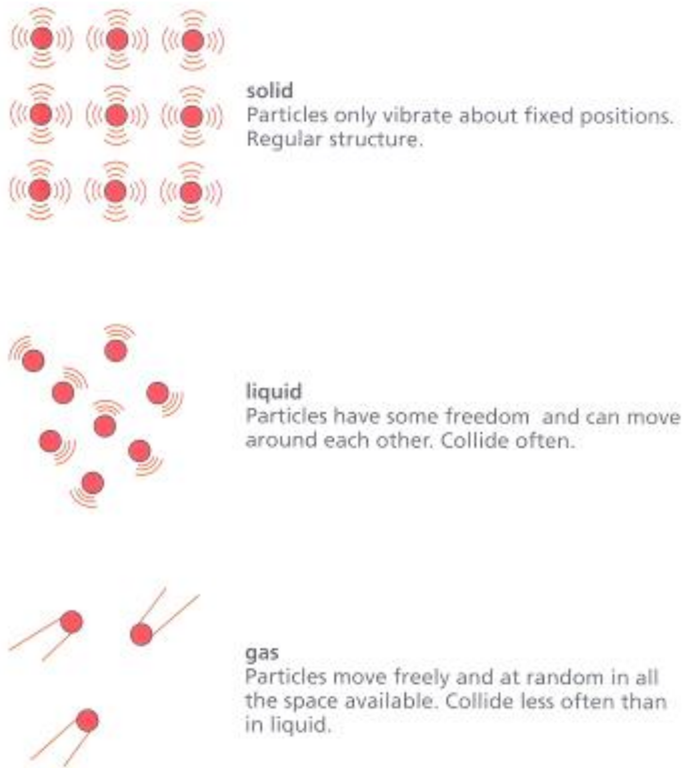


Figure 1.6 The arrangement of particles in solids, liquids and gases.

In a gas the particles are relatively far apart. They are free to move anywhere within the container in which they are held. They move randomly at very high velocities, much more rapidly than those in a liquid. They collide with each other, but less often than in a liquid, and they also collide with the walls of the container. They exert virtually no forces of attraction on each other because they are relatively far apart. Such forces, however, are very significant. If they did not exist we could not have solids or liquids.

The arrangement of particles in solids, liquids and gases is shown in Figure 1.6.

Questions

1 When a metal such as copper is heated it expands. Explain what happens to the metal particles as the solid metal expands.

2 Use your research skills on the Internet to find out about the technique of X-ray crystallography and how this technique can be used to determine the crystalline structure of solid substances such as sodium chloride.

Changes of state

The kinetic theory model can be used to explain how a substance changes from one state to another. If a solid is heated the particles vibrate faster as they gain energy. This makes them `push' their neighbouring particles further away from themselves. This causes an increase in the volume of the solid and the solid expands. Expansion has taken place.

Eventually, the heat energy causes the forces of attraction to weaken. The regular pattern of the structure breaks down. The particles can now move around each other. The solid has melted. The temperature at which this takes place is called the **melting point** of the substance. The temperature of a pure melting solid will not rise until it has all melted. When the substance has become a liquid there are still very significant forces of attraction between the particles, which is why it is a liquid and not a gas.

Solids which have high melting points have stronger forces of attraction between their particles than those which have low melting points. A list of some sub-stances with their corresponding melting and boiling points is shown in Table 1.1.

Table 1.1

Substance	Melting point/°C	Boiling point/°C
Aluminium	661	2467
Ethanol	-117	79
Magnesium oxide	2827	3627
Mercury	-30	~ 357
Methane	-182	-164
Oxygen	-218	-183
Sodium chloride	801	1413
Sulphur	113	445
Water	0	100

If the liquid is heated the particles will move around even faster as their average energy increases. Some particles at the surface of the liquid have enough energy to overcome the forces of attraction between them-selves and the other particles in the liquid and they escape to form a gas. The liquid begins to **evaporate** as a gas is formed.

Eventually, a temperature is reached at which the particles are trying to escape from the liquid so quickly that bubbles of gas actually start to form inside the bulk of the liquid. This temperature is called the **boiling point** of the substance. At the boiling point the pressure of the gas created above the liquid equals that in the air — **atmospheric pressure**.

Liquids with high boiling points have stronger forces between their particles than liquids with low boiling points.

When a gas is cooled the average energy of the particles decreases and the particles move closer together. The forces of attraction between the particles now become significant and cause the gas to **condense** into a liquid. When a liquid is cooled it **freezes** to form a solid. In each of these changes energy is given out.

Changes of state are examples of **physical changes**. Whenever a physical change of state occurs, the temperature remains constant during the change (see Heating and cooling curves, opposite). During a physical change no new substance is formed.

An unusual state of matter

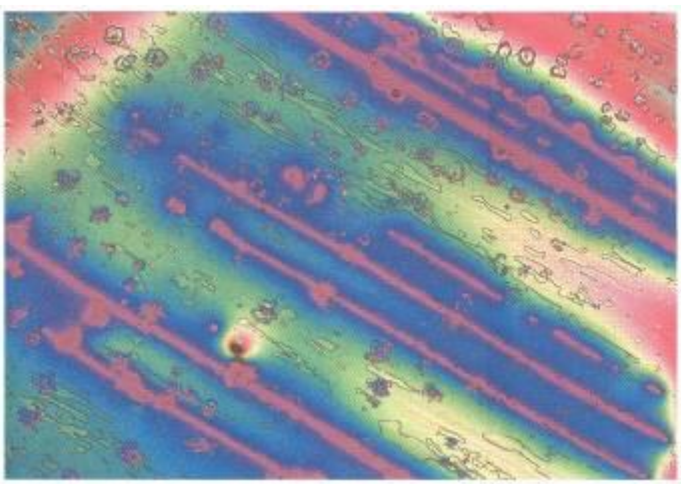


Figure 1.7 A polarised light micrograph of liquid crystals.

Liquid crystals are an unusual state of matter (Figure 1.7). These substances look like liquids, flow like liquids but have some order in the arrangement of the particles, and so in some ways they behave like crystals.

Liquid crystals are now part of our everyday life. They are widely used in displays for digital watches, calculators and lap-top computer displays (Figure 1.8), and in portable televisions. They are also useful in thermometers because liquid crystals change colour as the temperature rises and falls.

An unusual change of state

There are a few substances that when they are heated change directly from a solid to a gas without ever becoming a liquid. This rapid spreading out of the particles is called **sublimation**. Cooling causes a change from a gas directly back to a solid. Examples of substances that behave in this way are carbon dioxide (Figure 1.9) and iodine.

Figure 1.8 Liquid crystals are used in this computer display.

$$\text{solid} \underset{\text{sublimation}}{\overset{\text{sublimation}}{\rightleftharpoons}} \text{gas}$$

Figure 1.9 Dry ice (solid carbon dioxide) sublimes on heating and can be used to create special effects on stage.

Carbon dioxide is a white solid called dry ice at temperatures below -78°C. When heated to just above -78°C it changes into carbon dioxide gas. The changes of state are summarised in Figure 1.10.

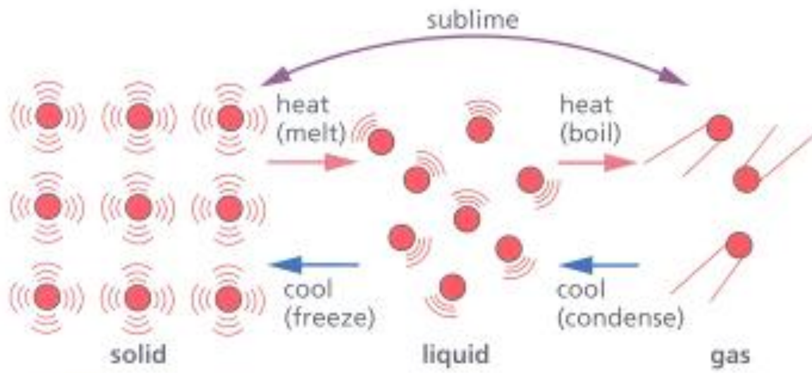


Figure 1.10 Summary of the changes of state.

Heating and cooling curves

The graph shown in Figure 1.11 was drawn by plotting the temperature of water as it was heated steadily from -15°C to 110°C. You can see from the curve that changes of state have taken place. When the temperature was first measured only ice was present. After a short space of time the curve flattens, showing that even though heat energy is being put in, the temperature remains constant.

In ice the particles of water are close together and are attracted to one another. For ice to melt the particles must obtain sufficient energy to overcome the forces of attraction between the water particles to allow relative movement to take place. This is where the heat energy is going.

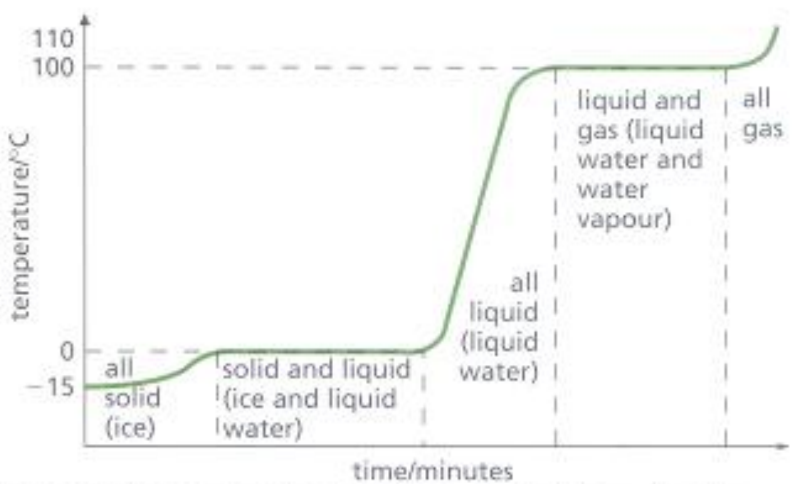


Figure 1.11 Graph of temperature against time for the change from ice at −15 °C to water to steam.

The temperature will begin to rise again only after all the ice has melted.

Generally, the heating curve for a pure solid always stops rising at its melting point and gives rise to a sharp melting point. The addition or presence of impurities lowers the melting point. You can try to find the melting point of a substance using the apparatus shown in Figure 1.12.

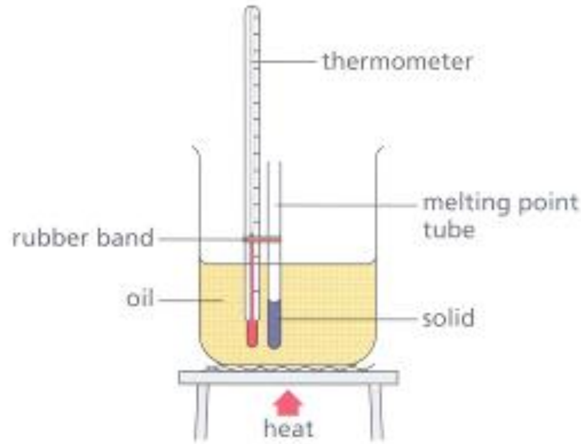


Figure 1.12 Apparatus shown here if heated slowly can be used to find the melting point of a substance such as the solid in the melting point tube.

In the same way, if you want to boil a liquid such as water you have to give it some extra energy. This can be seen on the graph (Figure 1.11) where the curve levels out at 100 °C — the boiling point of water.

The reverse processes of condensing and freezing occur on cooling. This time, however, energy is given out when the gas condenses to the liquid and the liquid freezes to give the solid.

Questions

1 Write down as many uses as you can for liquid crystals.

2 Why do gases expand more than solids for the same increase in temperature?

3 Ice on a car windscreen will disappear as you drive along, even without the heater on. Explain why this happens.

4 When salt is placed on ice the ice melts. Explain why this happens.

5 Draw and label the graph you would expect to produce if water at 100°C was allowed to cool to a temperature of -5°C.

Diffusion — evidence for moving particles

When you walk past a cosmetics counter in a department store you can usually smell the perfumes. For this to happen gas particles must be leaving open perfume bottles and be spreading out through the air in the store. This spreading out of a gas is called **diffusion** and it takes place in a haphazard and random way.

All gases diffuse to fill the space available to them. As you can see from Figure 1.13, after a day the brown—red fumes of gaseous bromine have spread evenly throughout both gas jars from the liquid present in the lower gas jar.

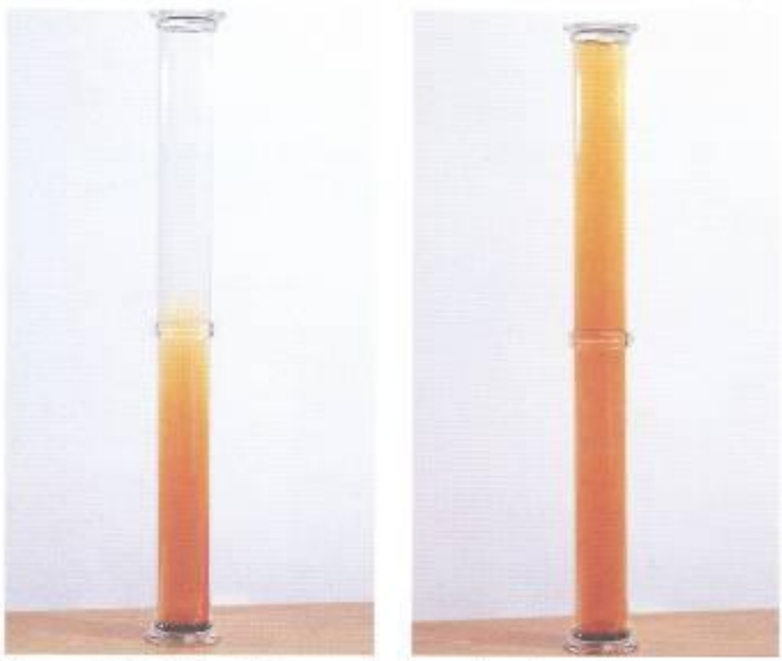


Figure 1.13 After 24 hours the bromine fumes have diffused throughout both gas jars.

Gases diffuse at different rates. If one piece of cotton wool is soaked in concentrated ammonia solution and another is soaked in concentrated hydrochloric acid and these are put at opposite ends of a dry glass tube, then after a few minutes a white cloud of ammonium chloride appears (Figure 1.14). This shows the position at which the two gases meet and react. The white cloud forms in the position shown because the ammonia particles are lighter than the hydrogen chloride particles (released from the hydrochloric acid) and so move faster. Generally, light particles move faster than heavier ones at a given temperature.

Diffusion also takes place in liquids (Figure 1.15) but it is a much slower process than in gases. This is because the particles of a liquid move much more slowly.

When diffusion takes place between a liquid and a gas it is known as **intimate mixing**. The kinetic theory can be used to explain this process. It states that collisions are taking place between particles in a liquid or a gas and that there is sufficient space between the particles of one substance for the particles of the other substance to move into.

Figure 1.14 Hydrochloric acid (left) and ammonia (right) diffuse at different rates.

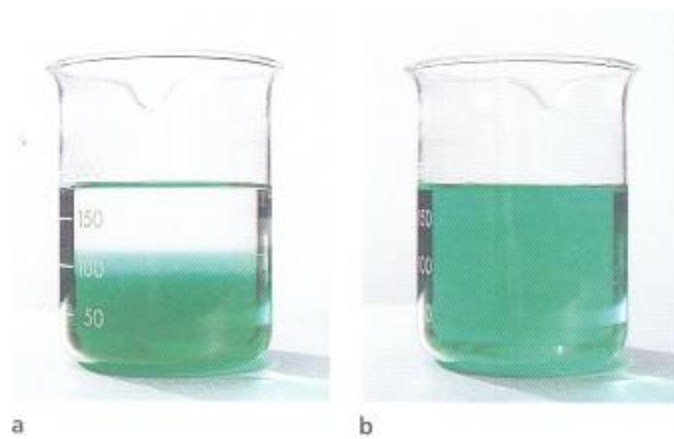


Figure 1.15 Diffusion within nickel(II) sulphate solution can take days to reach the stage shown on the right.

Brownian motion

Evidence for the movement of particles in liquids came to light in 1827 when a botanist, Robert Brown, observed that fine pollen grains on the surface of water were not stationary. Through his microscope he noticed that the grains were moving about in a random way. It was 96 years later,

in 1923, that another scientist called Norbert Wiener explained what Brown had observed. He said that the pollen grains were moving because the much smaller and faster-moving water particles were constantly colliding with them (Figure 1.16a).

a Pollen particles being bombarded by water molecules.

b Brownian motion causes the random motion of the visible particles.

Figure 1.16

This random motion of visible particles (pollen grains) caused by much smaller, invisible ones (water particles) is called **Brownian motion** (Figure 1.16b), after the scientist who first observed this phenomenon.

Questions

1 When a jar of coffee is opened, people in all parts of the room soon notice the smell. Use the kinetic theory to explain how this happens.

2 Describe, with the aid of diagrams, the diffusion of nickel(ii) sulphate solution.

3 Explain why diffusion in gases is faster than in liquids.

Gas laws

What do you think has caused the difference between the balloons in Figure 1.17?

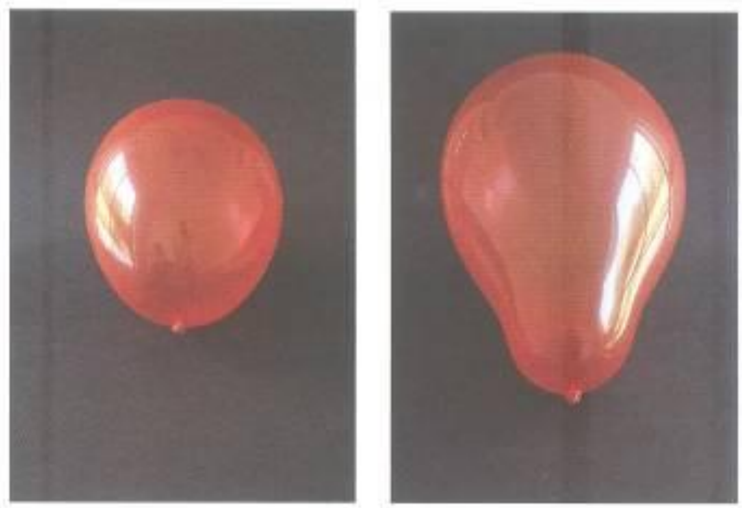


Figure 1.17 The balloon is partly inflated at room temperature (left) and becomes fully expanded at a higher temperature.

The **pressure** inside a balloon is caused by the gas particles striking the inside surface of the balloon (Figure 1.18). There is an increased pressure inside the balloon at a higher temperature due to the gas particles having more energy, moving around faster and so striking the inside surface of the balloon more frequently; this in turn leads to an increase in pressure. Since the balloon is an elastic envelope, the increased pressure causes the skin to stretch and the volume to increase. This increase in volume with increased temperature is a property of all gases. In 1781, from this sort of observation, a French scientist called Jacques Alexandre Cesar Charles concluded that when the temperature of a gas increased the volume also increased, at a constant pressure. This law is known as Charles' Law.

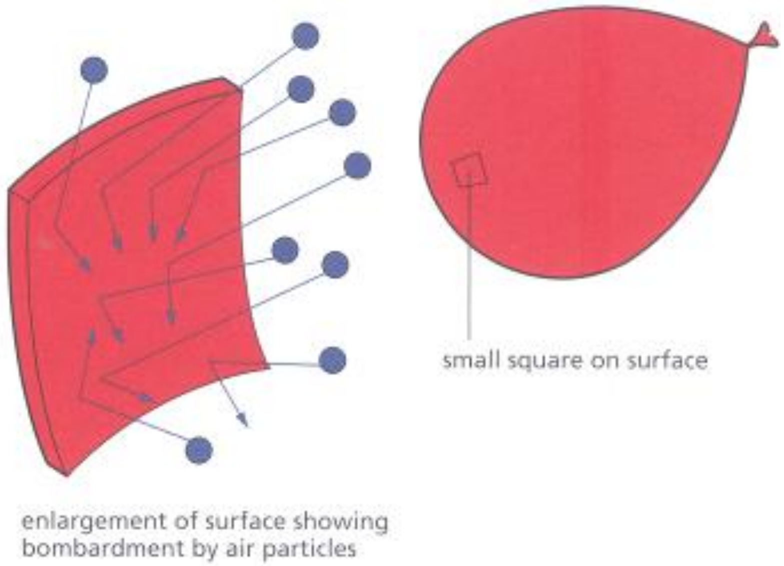
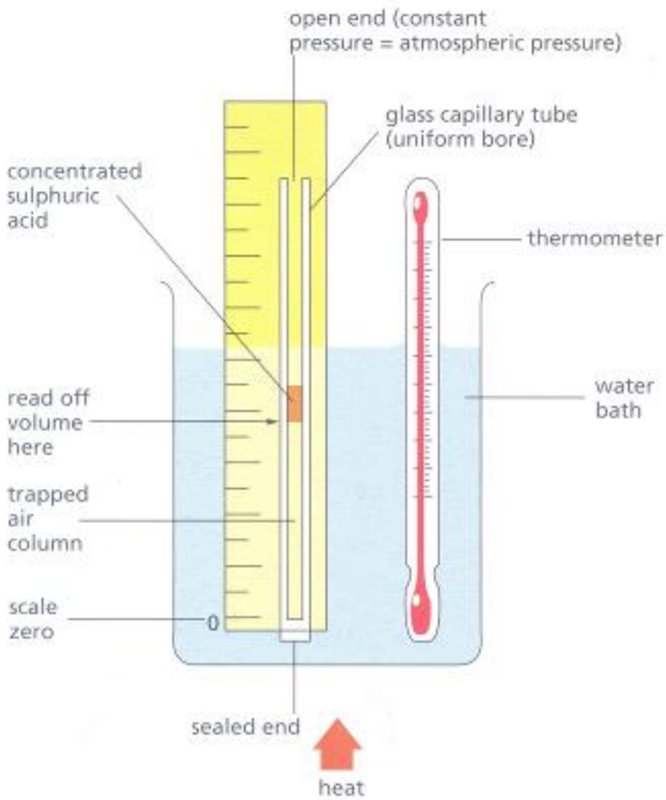
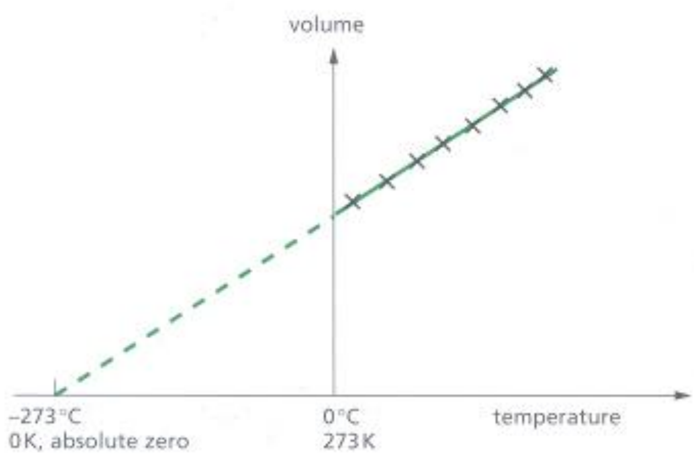


Figure 1.18 The gas particles striking the surface create the pressure.

Investigating Charles' Law



a Charles' Law apparatus.



b Graph of volume against temperature.

Figure 1.19

Charles' Law applies to a fixed mass of gas. The air column in the glass tube shown in Figure 1.19a has been trapped by a drop of concentrated acid, which moves up the tube as the gas expands. The length of the air column can be taken as a measure of the volume of air that is trapped. Readings are taken of the temperature and the length of the air column as the water bath is heated. If these data are plotted, then a volume against temperature graph like the one shown in Figure 1.19b is produced.

The graph shows that at -273 °C the volume of the gas should contract to zero! This temperature is called **absolute zero** and it is the lowest possible temperature. At this temperature, theoretically, particles have no motion and therefore possess no energy.

We can define a new temperature scale, which was proposed by Lord Kelvin in 1854, called the Kelvin scale of temperature, which has OK at absolute zero. Kelvins are the same size as degrees on the Celsius scale. On the Kelvin scale, water freezes at 273 K and boils at 373K. Note that

we write 273K without a ° (degree) sign. In general, to convert a Celsius temperature to a Kelvin temperature add 273.

$$K = °C + 273$$

Charles' Law states the volume, V, of a fixed mass of gas is directly proportional to its absolute temperature, T, if the pressure is kept constant. Later, it was found that a more accurate representation of Charles' Law required the temperature to be measured on the absolute temperature scale. Mathematically,

$$V \propto T$$

or

$$V = \text{constant} \times T$$

or

$$\frac{V}{T} = \text{constant } T$$

Boyle's Law

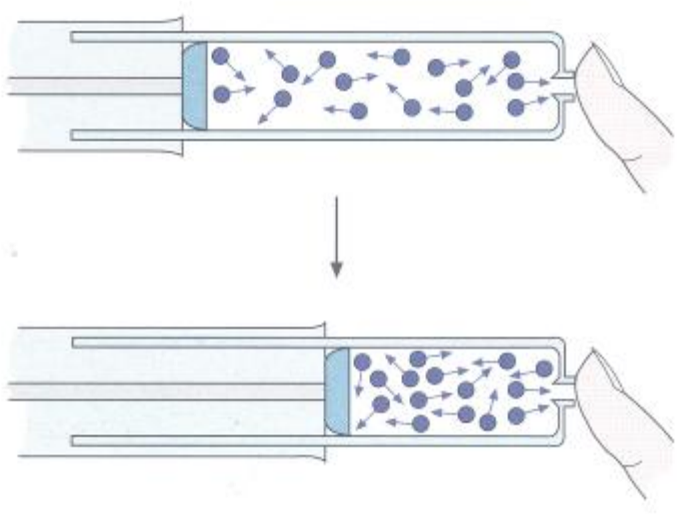


Figure 1.20 A higher pressure is created by pushing in the piston.

You can feel the increased pressure of a gas on your finger by pushing in the piston of a bicycle pump. As you push, you squash the same number of particles into a smaller volume (Figure 1.20). This squashing means they hit the walls of the pump more often so increasing the pressure.

In 1662 a scientist called Robert Boyle (Figure 1.21) deduced from experiments he carried out on various gases that when the pressure was increased, the volume of the gas was reduced.


Figure 1.21 Robert Boyle (1627–1691).

Why is it important to learn about how the volume of a gas changes with pressure? One popular use of this knowledge is in scuba diving (scuba stands for self-contained underwater breathing apparatus). To breathe under water, divers carry tanks of compressed gas (Figure 1.22). As they dive deeper, the water exerts more and more pressure on their bodies, and on the gas in their tanks. So that they can still breathe, the `air' in the tanks has to be regulated and the pressure reduced so that it is about the same as that in the surrounding water.

Divers can descend fairly quickly as the volume of air in their bodies decreases as the pressure increases. When they want to return to the surface, though, they have to take it slowly because from 10 m below the surface to the surface itself the pressure doubles. This means that if divers come up too quickly or while holding their breath they can burst their lungs.

Figure 1.22 Scuba diving can be dangerous even at shallow depths, as nitrogen in the compressed air can dissolve in body tissues and make the diver feel 'drunk'.

Investigating Boyle's Law

A car foot pump is used to increase the pressure on a fixed mass of air trapped by oil in a strong glass tube (Figure 1.23). The length of the air column is measured at different pressures.

A graph plotted of volume against 1/p gives a straight line through the origin. This demonstrates Boyle's Law, which states that the volume, V, of a fixed mass of gas is inversely proportional to its pressure, p, if the temperature is constant. Mathematically,

$$V \propto \frac{1}{p}$$

or

$$V = \frac{\text{constant}}{p}$$

or

$$pV = \text{constant}$$

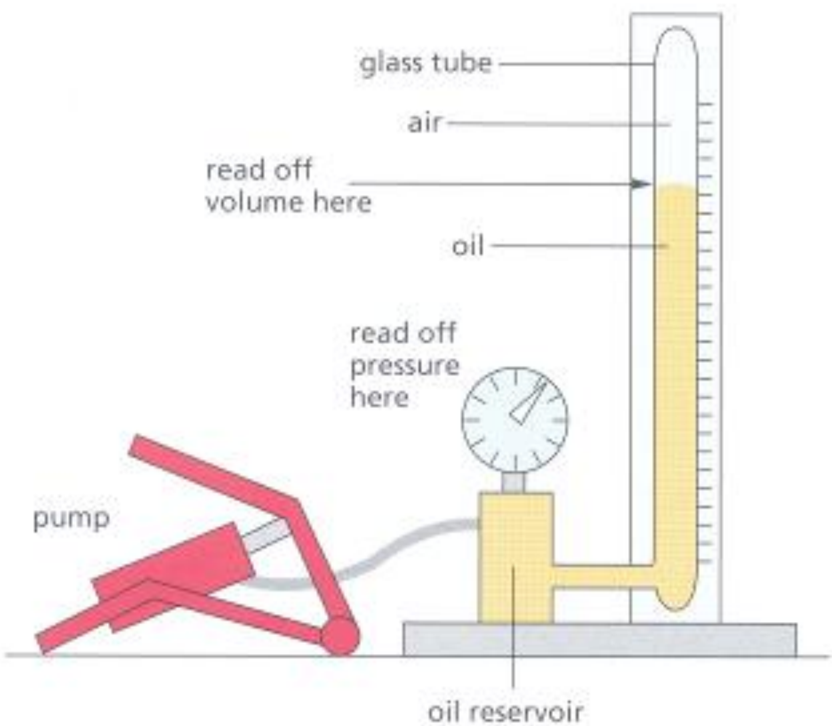


Figure 1.23 Boyle's Law apparatus.

Combining the gas laws

By combining Boyle's and Charles' Laws it is possible to show the relationship between the pressure, p, the volume, V, and the temperature, T, of a fixed mass of gas as:

$$\frac{pV}{T} = \text{constant}$$

or

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

where p_1, V_1 and T_1 and p_2, V_2 and T_2 are the pressure (in pascals), volume and temperature (in kelvin) in two different situations.

An example of the use of this relationship is given next. In the decomposition of hydrogen peroxide, if the volume of oxygen gas collected at 40°C and a pressure of 1×10^5 Pa was 100 cm^3, what would be the volume of the gas at a temperature of 10°C and a pressure of 2×10^5 Pa?

Using

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

$p_1 = 1 \times 10^5$ Pa | $p_2 = 2 \times 10^5$ Pa

$V_1 = 100\ cm^3$ | $V_2 = ?$

$T_1 = (40 + 273) = 313$ K | $T_2 = (10 + 273)$ K $= 283$ K

$$\frac{(1\times10^5)\times100}{313} = \frac{(2\times10^5)\times V_2}{283}$$

$$V_2 = \frac{(1\times10^5)\times100\times283}{313\times(2\times10^5)}$$

$$V_2 = 45.21\ cm^3$$

Questions

1 When a gas is heated the particles move more quickly. Explain what will happen to the volume of the heated gas if the pressure is kept constant.

2 A bubble of methane gas rises from the bottom of the North Sea.

a What will happen to the size of the bubble as it rises to the surface?

b Explain your answer to a.

3 A gas syringe contains $50cm^3$ of oxygen gas at 20°C. If the temperature was increased to 45°C, what would be the volume occupied by this gas, assuming constant pressure throughout?

4 A bicycle pump contains $50cm^3$ of air at a pressure of 1×10^5 Pa. What would be the volume of the air if the pressure was increased to 2.1×10^5 Pa at constant temperature?

5 If the volume of a gas collected at 60°C and 1×10^5 Pa pressure was 70 cm^3, what would be the volume at a temperature of 0°C and a pressure of 4×10^5 Pa?

Checklist

After studying Chapter 1 you should know and understand the following terms.

Absolute temperature A temperature measured with respect to absolute zero on the Kelvin scale. Absolute zero is the lowest possible temperature for all substances. The Kelvin scale is usually denoted by T.

$$T = °C + 273$$

Atmospheric pressure The pressure exerted by the atmosphere on the surface of the Earth due to the weight of the air.

Boiling point The temperature at which the pressure of the gas created above the liquid equals atmospheric pressure.

Boyle's Law At a constant temperature the volume of a given mass of gas is inversely proportional to the pressure.

$$V \propto \frac{1}{p}$$

Charles' Law At constant pressure the volume of a given mass of gas is directly proportional to the absolute temperature.

$$V \propto T$$

Condensation The change of a vapour or a gas into a liquid. This process is accompanied by the evolution of heat.

Diffusion The process by which different substances mix as a result of the random motions of their particles.

Evaporation A process occurring at the surface of a liquid involving the change of state of a liquid into a vapour at a temperature below the boiling point.

Kinetic theory A theory which accounts for the bulk properties of matter in

terms of the constituent particles.

Matter Anything which occupies space and has a mass.

Melting point The temperature at which a solid begins to liquefy. Pure substances have a sharp melting point.

Solids, liquids and gases The three states of matter to which all substances belong.

Sublimation The direct change of state from solid to gas and the reverse process.

All about matter

Additional questions

1a. Draw diagrams to show the arrangement of particles in:

(i) solid lead
(ii) molten lead
(iii) gaseous lead.

b. Explain how the particles move in these three states of matter.

c. Explain, using the kinetic theory, what happens to the particles in oxygen as it is cooled down.

2. Explain the meaning of each of the following terms. In your answer include an example to help with your explanation.

a. Expansion.
b. Contraction.
c. Physical change.
d. Sublimation.
e. Diffusion.
f. Random motion.
g. Brownian motion.

3a. Why do solids not diffuse?

b. Give two examples of diffusion of gases and liquids found in the house.

4. Use the kinetic theory to explain the following:

a. When you take a block of butter out of the fridge, it is quite hard. However, after 15 minutes it is soft enough to spread.

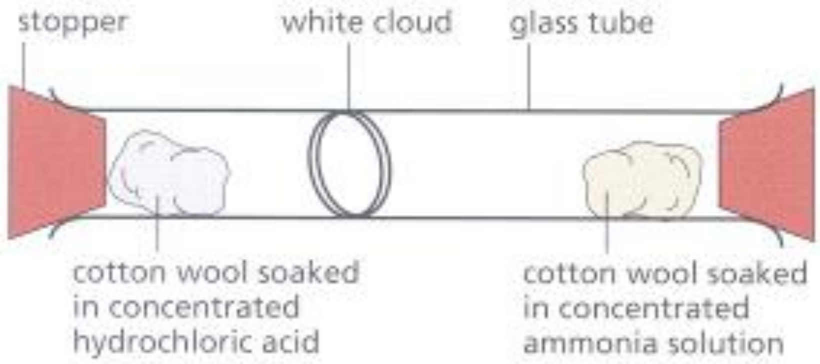
b. When you come home from school and open the door you can smell your tea being cooked.

c. A football is blown up until it is hard on a hot summer's day. In the evening the football feels softer.

d. When a person wearing perfume enters a room it takes several minutes for the smell to reach the back of the room.

e. A windy day is a good drying day.

5. The apparatus shown below was set up. Give explanations for the following observations.



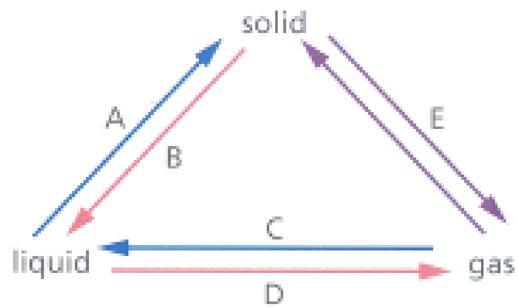
a. The formation of a white cloud.

b. It took a few minutes before the white cloud formed.

c. The white cloud formed further from the cotton wool soaked in ammonia.

d. Cooling the concentrated ammonia and hydrochloric acid before carrying out the experiment increased the time taken for the white cloud to form.

6. The following diagram shows the three states of matter and how they can be interchanged.



a. Name the changes A to E.

b. Name a substance which will undergo change E.

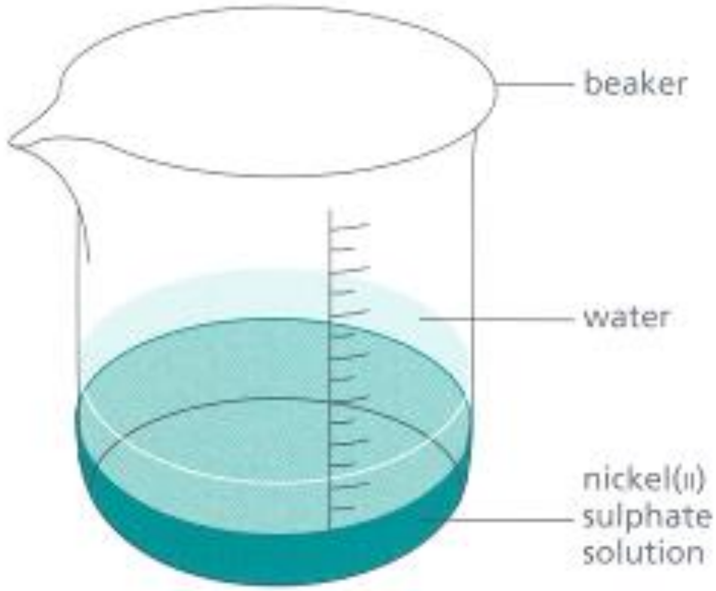
c. Name a substance which will undergo changes from solid to liquid to gas between 0°C and 100°C.

d. Describe what happens to the particles of the solid during change E.

e. Which of the changes A to E will involve:

(i) an input of heat energy?
(ii) an output of heat energy?

7. Some nickel(ii) sulphate solution was carefully placed in the bottom of a beaker of water. The beaker was then covered and left for several days.



a. Describe what you would see after:

(i) a few hours
(ii) several days.

b. Explain your answer to a using your ideas of the kinetic theory of particles.

c. What is the name of the physical process that takes place in this experiment?

8 An electric light bulb has a volume of 200 cm^3. It contains argon gas at a pressure of 1.1×10^5 Pa and a temperature of 25°C. When the light is switched on, the pressure increases to a steady 1.8×10^5 Pa. What is the temperature of the argon in the electric light bulb that creates this new steady pressure?